

AN INVESTIGATION OF THE FORMATION OF CAVITATION
ABOUT MODIFIED CYLINDRICAL MODELS

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LIST OF ABBREVIATIONS

- C - Centigrade.
- F - Fahrenheit.
- g - Acceleration due to gravity, feet/ sec.²
- Hg - Mercury.
- H₀ - Water.
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- H_t - Absolute pressure in the undisturbed liquid at the centerline of the working section, feet of liquid.
- H_v - Vapor pressure corresponding to the liquid temperature, feet of liquid.
- K - Cavitation parameter or coefficient.
- K_i - Incipient cavitation parameter.
- ρ - Mass density of the liquid in slugs per cubic foot.
- P_t - Absolute pressure in the undisturbed liquid at the centerline of the working section, pounds per square foot.
- W - Specific weight of the liquid in pounds per cubic foot.
- V - Relative velocity between the model and liquid, feet per second.
- Z - Elevation, feet.

-AN INVESTIGATION OF THE FORMATION OF CAVITATION
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INTRODUCTION
HISTORICAL SURVEY

The phenomenon of cavitation was first studied and described by Osborne Reynolds in 1894. The observation of the phenomenon had been carried out by Reynolds by means of a constriction in a tube through which water was flowing. Cavitation first appeared as an engineering problem about 1900. Its appearance in the marine engineering field was reflected as a loss of efficiency and destruction of propeller materials, when higher propeller speeds resulted upon the advent of the use of steam turbine drive for ship propulsion. The deleterious effects of this phenomenon were also encountered in the mechanical engineering field shortly afterwards as the speeds of turbines and pumps increased.

In 1896 during the trial tests of the British torpedo-boat Daring, maximum designed speed was not reached. Although the exact cause was not known at that time, it is now known that the loss of efficiency was due to cavitation. A description of the destruction of the screw propellers of the fast steam-boats, the Lusitania and Maurentania, was given by Silberad²⁷ in 1912. Additional examples of the destruction of screw pro-

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pellers were given by Ramsey within the same year. In all cases reported the destruction occurred only upon the motion of the ship, and in several cases a running time of only a few hours was necessary to render the propeller completely unfit for work.

The British Admiralty established a commission in 1915 to study the cause of the destruction of ship propellers. The destruction of the propellers according to Parsons and Cook²⁰ resulted from repeated hydraulic blows, resulting from the collapse of cavities. At a later date Föttinger⁷ arrived at the same conclusion in his observation of the destruction of hydraulic structures in the mechanical engineering field.

An attempt to explain the destructive effect of cavities was first made by Cook. Somewhat later Rayleigh²³ improved the theory of Cook by modifying it to a more general case. Parsons and Cook also started the experimental investigation of the problem of cavitation destruction by means of the flow of water through a pipe in which a local constriction had been placed; however, these experiments were not successful. Several years later this study was continued by Föttinger, then Schrotter, Haller⁹, and Mousson¹⁹ by using similar apparatus, but a type which was much more effective due to the use of a reduced cross section of a narrow part of the constriction and increased water velocity. A specimen of material was placed in the path of the cavities; and using various

metals and alloys, intensive destructive action was obtained in a period of time varying from 10 to 100 hours.

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In 1932 Gaines developed a new method of obtaining cavitation destruction by making use of the magnetostriction effect. By excited, intense, longitudinal vibrations in a nickel rod when submerged in water, Gaines obtained cavities on the end of the rod and subsequent intensive destruction. The destructive effects by this method are caused by the variable pressures, which arise in the water near the vibrating end of the rod. Cavities are formed during that part of the period in which the pressure falls to a value corresponding to the vapor pressure. In the remaining part of the period, the pressure increases, thus causing the collapse and disappearance of the cavities. The method used by Gaines was ¹² improved by Hunsaker¹⁴, which improvement was used by Kerr to obtain intensive destruction of various metals and alloys during a time interval of about 1 hour.

In all of the foregoing experimentation accent was placed upon the destructive effect of cavitation, what caused it, and how to prevent it. In recent years, however, attention has been focused upon the investigation of the complete life history of cavitation from initial formation through to final collapse. The main type of apparatus used for this study is the variable pressure, variable flow, water tunnel. Useful because of the ease of control of the intensity of

cavitation, making possible photographic studies of models, this type of apparatus is now being used in various places; notably, the U. S. Experiment Model Basin, the David Taylor Model Basin, the California Institution of Technology, and the University of Iowa.

THE NATURE OF CAVITATION

Two terms which are used frequently in literature on cavitation are "cavities" and "pitting." Since liquids, which are encountered in engineering practice, can not support appreciable tension stresses, cavities will form in them wherever the absolute pressure approaches closely to the vapor pressure of the liquid. A cavity thus forms in the liquid. Pitting is the destruction and subsequent erosion of materials by cavitation action, occurring on the solid boundary, not in the liquid. Although pitting has been attributed to chemical action, electrochemical action or corrosion, high tension in the water, and other reasons, this destruction is presently thought to be essentially a mechanical one, resulting from the impact of solid liquid masses on the surface of the material.

Since cavities are formed by a reduction of pressure, two factors contributing to pressure reductions may be seen from the Bernoulli equation for a frictionless fluid:

$$\frac{P}{w} + \frac{V^2}{2g} + Z = \text{constant}$$

- which are increments of velocity, V , and of elevation, Z . The other symbols are defined as follows: P is the pressure per unit area; w is the specific weight; and g is the acceleration due to gravity.

A consideration of the effects due to elevation reveals that cavitation will most likely appear at the top of a conduit rather than at the bottom, or at a region of lower pressure due to elevation. Other examples illustrating the effect of elevation are the hydraulic turbine, in which the tendency for cavitation will increase with the higher setting of the turbine above the tail water, and the marine propeller, on which the tendency for cavitation is more pronounced upon the propeller of a surface vessel than the propeller of a submarine.

The pressure reduction resulting from velocity increments is usually caused by the constriction of a passage; familiar examples are the venturi meter and the aspirator nozzle.

A factor that is not revealed in the Bernoulli equation is flow curvature, which may result from the following examples: an orifice; bell mouth entrance; vortex; abrupt obstruction; or curved flow in such apparatus as a pipe elbow. Flow curvature may be accompanied by the occurrence of separation, eddies, vortices, boundary layer phenomena, resulting from viscous action. The cavitation that is formed in this manner is unpredictable and irregular.

Fottinger derived the following conclusions concerning the life events of cavitation from photographs taken at the Massachusetts Institute of Technology at Cambridge, Massachusetts: (1) the formation of the cavity; (2) the travel of the cavity; (3) the final collapse; and (4) the

result of the collapse. These conclusions indicate that the cavity forms in a region of low pressure, breaks away from the point of formation, is swept to a region of higher pressure, collapses, and causes pitting due to some mechanical action resulting in extremely high pressures. Knapp and Hollander¹⁵ in their studies at the California Institute of Technology included in the life history of a cavity each succeeding rebound and recollapse phase through to the final collapse and final disappearance.

In the ordinary engineering liquid a quantity of air or other gases may be dissolved. In regions of low pressure it would be expected that there would be a tendency for these gases to come out of solution. For this reason it would be suspected that the pressure existing within cavities would be somewhat greater than the vapor pressure of the liquid by an amount equivalent to the partial pressure of the gases released into the cavity. That this observation is true has been proven by experimentation. A further observation included in the study was the fact that increased air content increased the pressure within the cavity. According to Knapp and Hollander the only gas which would come out of solution into the cavity would be from that dissolved in a very thin layer adjoining the bubble surface. According to their calculations, assuming a 2% by volume

saturation of the water by air and using the time of 0.0022 seconds, for maximum bubble growth, at which they arrived experimentally, the partial pressure of the air is 0.3 mm. mercury. Thus their conclusion was that the cavities essentially contained only water vapor with a very minute quantity of released gas.

Hunsaker discovered that whenever cavities are formed by separation from divergent boundaries, the frequency of formation is somewhat regular, approximately proportional to the velocity of flow and inversely proportional to the length of the cavity. It was found that there is no regularity in the formation and collapse of cavities caused by a vortex. In perfectly steady flow it should be expected that there would be no collapse; however, turbulence of flow causes disrupting of the cavity from the vortex, small portions of which are swept to regions of higher pressure and are collapsed.

Cavitation may also be formed by means of eddies, resulting usually from the flow about boundary irregularities, in which case the cavities are swept along by the stream to regions of higher pressure. Cavities may also be formed as a result of an exceedingly small gaseous bubble serving as a nucleus of formation.

The thermodynamic processes of cavitation are not known quantitatively. It is generally assumed, except in the case of cavitation due to a fixed vortex, that there is

no stability. There has been, as yet, no relations set up correlating the release of absorbed gases and the vaporization of the liquid upon the formation of cavitation, except for the work of Knapp and Hollander, who showed that for an assumed shell thickness about the cavity as a source of heat the shell thickness of the evaporated portion is almost seven times as large. Their conclusion was that the theory of the migration of air to the cavity across a shell seven times as great as the heating shell would be very improbable; whereas the evaporative process appeared very plausible.

Upon the formation of a cavity its travel to the point of collapse is usually characterized by a speed less than that of the liquid, usually approximately in the ratio of one-half, except in the case of cavities formed by eddies, in which case the speed of travel of the cavities approaches that of the liquid.

Cavity collapse is the result of a retardation of the downstream face upon entering regions of higher pressure; the effect of the difference of velocity between the upstream and downstream face is to flatten the cavity.

Knapp and Hollander in the study of the formation, growth, and collapse of a single bubble found that during the time between initial formation and initial collapse formation required about three-fourths of this time, leaving one-fourth for the collapse. During the final stages

of the first collapse it was found that the leading edge of the bubble was moving radially inward so fast that it was actually moving upstream in the tunnel.

The destructive action or pitting of the solid boundary, which results from the collapse of the cavity, is attributed by the authorities to two different mechanical actions. It is held by some that the destructive effect of the cavity is due to the momentum of the inward rushing liquid being reduced to zero in an almost infinitesimal time, and if occurring on a solid boundary, the pressure on an infinitesimal area becomes enormous, capable of denting and eventually destroying the material. Lord Rayleigh²³ developed an equation expressing pressures developed upon the collapse of a cavity in this manner, assuming the cavity to remain spherical throughout the collapse period. Whenever the diameter of the cavity has been reduced $1/20$ and $1/100$, according to Rayleigh the pressures are respectively 68 and 765 tons per square inch. That intensely high pressures do exist on small areas has been demonstrated by means of piezoelectric crystals; however, the pressures which actually occur on minute areas are probably much higher than those found by means of the crystals, since photographs have shown the area of each individual pit to be much smaller than the area of the crystal.

Other authorities attribute the destructive action of cavitation to the formation of minute slugs of liquid within the cavity, to which is imparted a high velocity upon the collapse of the cavity. That destruction could easily result from such a bombardment of liquid particles is readily seen. Photographs have been taken which show that upon collapse the cavity does contain droplets of the liquid - a confirmation of this theory. The theory, however, is held by Vennard³² that pitting is probably the result of a combination of the actions described in the two theories, the bubble collapse theory and the impact of small liquid masses.

The collapse of the cavity is accompanied by the thermodynamic processes, the high-speed compression of the gases within the cavity and the condensation of the liquid vapor. It is thought by Vennard that although high temperatures ordinarily would accompany such changes, that the opposing factors favorable to cooling, the expansion of the gases and vaporization of the liquid upon the formation of the cavity, and the usual great volume of the liquid in the surroundings to carry away any heat generated, would prevent any appreciable local temperature change; thus it is doubtful that thermal effects could play an important part in the pitting of materials.

It should be expected that the effect of gas content would play an important part in pitting action. Gas content in increased amounts could be expected to cause greater resistance to the collapse of the cavity due to a decreased rate of reabsorption of the gases by the liquid and a slowing of the condensation of the liquid vapor. That increased air content does produce a cushioning effect upon the collapse and reduces pitting has been proven experimentally.

The finish of the surface of the boundary subject to pitting is a variable in the speed of pitting action. Tests have shown that rough surfaces are invariably destroyed much faster than smooth surfaces. Experience has also shown that as the smooth surface of a material is destroyed, cavitation action increases, yet at times has apparently brought about a condition that has stopped itself, probably due to the forming of a water cushion in the eroded region, preventing collapse on the boundary surface.

One explanation for the accelerated pitting on a rough surface is that the nucleus of the cavity is driven into the fissures of the irregular surface and whenever the pressure of the surrounding region drops, explodes, causing the excessive damage of the surface. Another explanation is that the inner ends of the fissures serve as cavities, which upon the collapse of cavities on the outer surface and increase of pressure, collapse themselves, causing intense destructive action. A further explanation is that the inner end of the

fissure is subject to intense local pressures caused by the reflection of a pressure wave, resulting from the collapse of cavities on or near the opposite end of the fissure. Experiments by Poulter have shown that intermolecular penetration of the boundary by a liquid is able to cause destruction of the solid upon release of the pressure on the liquid. These experiments, however, were carried out over a relatively long period of time, and it is probable that they bear no significant relation to cavitation pitting, in which the high pressures exist for very short periods of time. Mousson has also conducted experiments that show no accelerated pitting on the solid, where cracks are present on the surface. It was further shown by Mousson that the solid beneath the surface weakened before cracks appeared on the surface, as a result of blows on the surface.

PURPOSE

It is the purpose of this thesis study to experiment with a pilot model of a variable pressure water tunnel, making possible the detailed study of the formation and collapse of cavitation bubbles.

In the section entitled "Nature of Cavitation" has been included the theories that some of the authorities on cavitation have conceived. It is notable that in many cases there is scant evidence to back up these various theories, and between the various authorities there is in some cases a partial disagreement. This lack of knowledge is due to the inherent difficulty of observing cavitation and measuring the physical properties, or perhaps the change in physical properties, throughout the life history of cavitation. It will be a sufficient illustration to cite the report by Knapp and Hollander that the approximate time between the initial formation of the cavity to its initial collapse is 0.003 seconds. Due to this reason, the majority of the studies that have been carried out until recently have been to study the cause and nature of pitting, how to control it by correct designing of hydraulic machinery and structures, and the recording of cavitation by relatively slow motion pictures or still pictures.

In this study motion pictures have been taken at 64 frames per second of the formation of cavitation about

modified cylindrical models. The models, four in number, have geometrical shapes as follows: (a) bevelled nose and boat-tail afterbody; (b) bevelled nose and cylindrical afterbody; (c) blunt nose and boat-tail afterbody; and (d) blunt nose and cylindrical afterbody. It is of particular importance to determine the point of incipient cavitation in order to determine at what speed in air separation occurs about the models.

In order to obtain photographic records of cavitation, it is necessary to provide conditions by which the desired degree of cavitation may be measured and reproduced. There is visible evidence on observing cavitation about a model that the length of the cavitation pocket at the top is greater than at the bottom. This directly infers that cavitation is decidedly affected by minute pressure changes since the change of pressure due to elevation is very small. This observation gives substance to the decision to use Thoma's cavitation parameter to set the degree of cavitation for taking motion pictures. Thoma's cavitation parameter is defined as follows:

$$K = \frac{\frac{P_t - P_v}{\rho \frac{V^2}{2}}}{\frac{H_t - H_v}{\frac{V^2}{2g}}}$$

in which:

K - Cavitation parameter.

P_t - Absolute pressure in the undisturbed liquid at the centerline of the working section, lbs./ sq.ft.

H_t - Same as P_t in ft. of liquid; $H_t = \frac{P_t}{\omega}$

P_v - Vapor pressure corresponding to the liquid temperature.

H_v - Same as P_v in ft. of liquid; $H_v = \frac{P_v}{\omega}$

V - Relative velocity between the model and liquid, ft./ sec.

ρ - Mass density of the liquid in slugs per cu. ft.

$$= \frac{w}{g}.$$

w - Specific weight of the liquid in lbs. per cu. ft.

g - Acceleration due to gravity, ft./ sec.²

EQUIPMENT AND EQUIPMENT OPERATION

The experimental studies carried out in this thesis have been conducted in a pilot model of a variable pressure water tunnel in the Hydraulics Laboratory of the Civil Engineering Department. The design of the apparatus was done by Professor C. E. Kindsvater. The apparatus is intended for student use in the undergraduate school as soon as the undesirable conditions of the apparatus are eliminated.

The arrangement of water tunnels may be classified in the same way as wind tunnels as open-circuit or as closed-circuit type. Since there is usually no ready, inexpensive, unlimited reservoir of water to draw upon, the open-circuit type is not to be found in use. The closed-circuit, return-flow type of apparatus, in which the water is circulated through a closed loop, is the only practical type of water tunnel. For this reason the design of the pilot model has been made of the closed-circuit type.

The type of working sections in water tunnels have also been classified in the same manner as those in wind tunnels. They are the open-jet and the closed-jet type. In the open-jet type the water discharges through a nozzle into a chamber, which has a cross section somewhat larger than the cross section of the jet. This arrangement has the advantage that the static pressure over the length of the working section is constant. In the closed-jet type of

apparatus the advantage is that it provides steadier flow conditions, although producing the undesirable condition in some cases of an appreciable pressure drop in the direction of flow in the working section. In order to facilitate simplicity of design, ascertaining the purpose of the pilot model, the closed-jet type of working section was used.

An overall sketch of the apparatus may be found on page 36, Figure 4. Photographs of the apparatus may be found as follows: Figure 12, page 44; Figure 13, page 45; Figure 14, page 46; Figure 15, page 47.

The most important functions of the entire apparatus are centered in the working section. The working section consists of a two foot section of circular three inch nominal diameter lucite tubing. Lucite obviously provides an excellent means of observing and photographing the phenomena of cavitation. The cylindrical models are supported in the working section on a threaded rod, which is supported by straightening vanes connected to a flange, which fits between the working section and a shorter section of lucite tubing. To preserve the pressure-tight integrity of the system rubber-cork flanges or rubber-cloth flanges surfaced by caulking compound have been used. Two piezometer openings, lying in a straight line perpendicular to the centerline of the working section, have been con-

nected to a mercury manometer, by which the gage pressure of the working section may be measured.

Since the velocity head is obtained from readings of the pressure differential taken from a bendmeter, it is important that the velocity head be uniform across the working section. In order that the velocity might be uniform a honeycomb baffle was placed in the tank, extending to the reducer nozzle flange. A velocity traverse was taken across the working section to determine the effectiveness of this setup. Figure 1, page 33, shows the setup used in determining the velocity traverse. The baffling system proved to be very effective, as is shown by Figure 2, page 34. The reducer nozzle has such a curvature that provides a continuous pressure drop in the direction of motion; thus the flow is accelerated just before it enters the working section, providing a uniform axial velocity profile.

The tank is used as a collecting point for entrained air and as a reservoir of water. Connected to the top of the tank is a pressure gage, measuring the absolute pressure of the vapor and the trapped air. An air ejector, also connected to the top of the tank, is used to provide pressures approaching -30 feet of water. A lucite tube, connected to the top of the tank and extending approximately three-fourths of the distance to the bottom of the tank, is used as a water level indicator. A baffle at the entrance

of flow in the bottom of the tank is used to turn the flow radially outward.

A centrifugal pump is used to circulate the water through the system, and an induction motor is used to provide the input power to the pump. A gate valve is used to vary the flow.

One of the six inch pipe elbows has been used as a bendmeter to determine the flow rate. Figure 3, page 35, is a sketch of the apparatus used to calibrate the bendmeter. The car, shown in the sketch, was used to shift the water from the weighing tank to the drain. The duration of time of flow of a qualified amount of water was taken from stopwatch readings of successive trippings of the scales, which sequence was arranged by changing the scale reading. Temperature readings of the water and the pressure differential between the inner and outer radii of the elbow were taken at regular intervals of time. With this data calculations were made and a curve was plotted with flow versus pressure differential. As it was expected, this curve approximated a parabola, which is illustrated by Figure 5, page 37. Furthermore, Figure 6, page 38, bears out that the velocity head versus the pressure differential is a straight line relation. An air-water manometer has been used to determine the pressure differential caused by the bendmeter.

A bimetal thermometer with the metal union inserted into the tank has been used to measure the temperature of the water in order that the vapor pressure of the water might be determined.

Below is given a list, including size, serial number, and manufacturer of various parts of the apparatus:

1. Water-mercury manometer, Meriam Instrument Co., No. 31114, 30 inch scale.
2. Air-water manometer, Meriam Instrument Co., 36 inch scale.
3. Weston bimetal thermometer, Fahrenheit scale, 0 to 180 degrees.
4. Motor, line start induction, Allis Chalmers Manufacturing Co., Type ARX, Frame No. 284y, 10 HP for 24 hors at 40 degrees C, 3 phase, 60 cycle, 3500 RPM, Serial No. 711PC-N15657-30.
5. Pump, centrifugal, Allis Chalmers Mfg. Co. Size 3-2-1/4, 225 GPM, Type SSDh, 125 foot head, Runner diameter- 6 inches, Speed - 3500 RPM.
6. Motor control, Condit Electrical Manufacturing Co. for Allis Chalmers Manufacturing Co.

The operational difficulties encountered in the use of the equipment were, unfortunately, of a repeated nature. The source of practically all the difficulties was the inability to run the apparatus until it had reached a point of heat equilibrium; that is, the heat input rate of the pump equaling the heat loss rate of the apparatus. Since the total volume of water circulated was relatively small, the temperature of the water climbed steadily until structural failure, loss of vacuum, or other trouble arose to discon-

tinue the operation.

It was found that a water-carbon tetrachloride manometer was not satisfactory after the water in the system became heated due to vaporization of the carbon tetrachloride and collection of bubbles between the water and carbon tetrachloride adjoining faces. It was also found that the use of vacuum wax on threaded lucite joints was troublesome because of the wax melting whenever the water became heated from operation. A more satisfactory compound was found to be a fibrous, white, caulking compound. It was further found that, after becoming sufficiently heated, very little concentrated heat is needed to seriously warp lucite tubing, as was experienced by placing a photo-flood lamp near the working section and consequently producing a very visible sag and flattening of the tube. The rising temperature caused a constantly changing cavitation number.

The apparatus was run until the temperature reached 165 degrees F. Since the rate at which the temperature rose did not indicate that equilibrium would be reached at a safe temperature, it was necessary to run the apparatus for short periods of time.

Other troubles, incidental to the running of the equipment, were the overheating of the electric motor, the burning out of the packing in the pump, corrosion and subsequent weakening of the model support, and the depositing

of a film precipitated from the water during the deaeration process upon the lucite working section, impairing the good photographic qualities of the setup. The overheating of the electric motor, attributed by an electrician to damp windings, was overcome after running the motor a considerable length of time. A special type of packing was found to be necessary for the pump. A non-corrosive rod was placed in the model support, eliminating the source of trouble. The only answer to the film collection on the lucite tubing was washing, a process requiring care since lucite is easily scratched.

DISCUSSION

PROCEDURE

Each of the cylindrical models was placed in the working section of the pilot model. Thoma's cavitation parameter, K , was changed until observation indicated the points of incipient cavitation for both the nose and the tail of each of the models. Standard motion pictures were taken of each of the models at four different values of K . The method used in changing K is given below.

Figure 6, page 38, gives the bendmeter differential head in terms of the velocity head, $\frac{V^2}{2g}$, in the working section. Figure 7, page 39, gives the relation between the saturation pressure of water and the temperature of the water, taken from Keenan and Keyes Steam Tables; thus the vapor pressure, H_v , can be gotten immediately from the graph for the indicated temperature. Figure 8, page 40, converts the reading of the centerline gage pressure of the working section from inches of mercury to feet of water. The absolute pressure is found by getting the algebraic sum of the barometric pressure and the gage pressure. Figures 9, 10, and 11 on respectively pages 41, 42, and 43 are graphs by which cavitation numbers are given in relation to the velocity head and absolute centerline of working section pressure minus vapor pressure, each in feet of water.

The incipient cavitation numbers of the nose and tail of each model were determined by using Figures 6-10.

By experimentation it was found that a velocity head of 2 in the working section was very convenient to use for setting up a sequence of cavitation numbers for the taking of motion pictures for each model from the first point of incipient cavitation; that is, tail or head, to a point of extreme cavitation. From Figure 6 the bendmeter differential head was set up for a velocity head of 2. Then in successive increments the vacuum pressure in the working section was increased until a visible evidence of cavitation about the nose or tail was first noticeable. At this point the reading of the working section manometer was taken, converted by Figure 8 from inches of mercury to feet of water. This figure was subtracted from the barometric pressure in feet of water to obtain the absolute head in the working section, H_t . Also, at this point the temperature was read, and by means of Figure 7 the vapor pressure, H_v , in feet of water obtained. The vapor pressure was subtracted from the absolute pressure of the working section, $H_t - H_v$. For a velocity head of 2 and for the particular value of $H_t - H_v$ in question a value of K was determined from either Figure 9, 10, or 11. It was necessary to repeat this process many times until consistency of results showed that the deaeration of the water was practically complete. For the setting of a particular value of K the above process was carried out in reverse.

RESULTS

Below is given a tabulation of the results obtained in determining the points for incipient cavitation for each of the models.

K_1	$V^2/2g$	H_t	T_v	H_v	$H_t - H_v$	Point of Incipience
-------	----------	-------	-------	-------	-------------	---------------------

Bevelled Nose, Boat-Tail Afterbody Model

2	2	5.54	89	1.55	3.99	Tail
---	---	------	----	------	------	------

2	2	5.54	89	1.55	3.99	Nose
---	---	------	----	------	------	------

Bevelled Nose, Cylindrical Afterbody Model

2	2	6.00	97	2.00	4.00	Tail
---	---	------	----	------	------	------

2	2	6.00	97	2.00	4.00	Nose
---	---	------	----	------	------	------

Blunt Nose, Boat-Tail Afterbody Model

2.5	2	7.52	105	2.52	5.00	Tail
-----	---	------	-----	------	------	------

2.7	2	8.00	106	2.60	5.40	Nose
-----	---	------	-----	------	------	------

Blunt Nose, Cylindrical Afterbody Model

2.5	2	7.45	104	2.45	5.00	Tail
-----	---	------	-----	------	------	------

2.7	2	8.00	106	2.60	5.40	Nose
-----	---	------	-----	------	------	------

Pictures of each of the models are given in Figures 20, 21, 22, and 23, on respectively pages 49, 50, 51, and 52, in which the cavitation parameter, K , was set at 1.25.

CONCLUSIONS

No success was had in the attempt to photograph incipient cavitation. The data, that has been included in the results, has been taken entirely from experiments in which the incipient cavitation number is that condition at which cavitation is first visible. Observations have shown that there is no apparent delay in the formation of cavitation about the model with the boat-tail afterbody over the model with the cylindrical afterbody. In all observations taken the point of incipient cavitation referred to as "tail" occurred aft of the model. The use of a bevelled nose provided a lower incipient cavitation number than the blunt nose. The point of incipience for the bevelled nose apparently occurred at the inner ring of the bevelled edge. The point of incipience for the blunt nose apparently occurred at the leading edge of the model. These results indicate no improvement of the boat-tail afterbody over the cylindrical afterbody in the lowering of the point of incipient cavitation; however, the bevelled nose appears to be a decided improvement over the blunt nose.

At points where the cavitation envelope was more fully developed the envelope appears to have a smaller volume for the bevelled nose models than the blunt nose models for the same cavitation parameter. No effect was noticed from the use of a boat-tail afterbody rather than a cylin-

drical afterbody at conditions of extreme cavitation. Observations and photographs indicate that the cavitation envelope begins at the leading edge of both the blunt nose and bevelled nose models and sweeps back, giving the approximate appearance of a paraboloid with a plane passed perpendicular to the axis through the latus rectum. This condition may be observed in Figures 20, 21, 22, and 23 on respectively pages 49, 50, 51, and 52.

Although it is believed that the point of incipient cavitation of the model in water corresponds to the point of separation on the prototype in air, no definite proof has been established that this is true. For this reason no attempt has been made to determine the relative velocity the model would have in air upon the beginning of separation from the data given for incipient cavitation. The water tunnel, however, may be used as a means of establishing a shape for the model for the conditions desired. By observing the cavitation number and the point of incipience on any given model, modifications may be made on successive models to determine the effect of certain geometric configurations. Since the lowest cavitation number which the pilot model can produce is about 0.8, it is suggested that possibly the apparatus should have to be modified to produce a lower K_i in experiments with more streamlined models than were used in this test.

Since Knapp and Hollander indicate that moment, drag, and lift coefficients may be determined from water tunnel tests corresponding closely to results obtained in wind tunnel tests without correcting for tare or scale effects, it is suggested that in future experiments valuable information may be gained by placing the model support upon a system of balances to determine the various forces acting on the model. It is further suggested for future work that piezometers be used to determine the pressure distribution about the model. Better photographic results than those obtained can be had by increasing the rate to at least 10,000 frames per second, which indicates a subsequent reduction in the exposure time. The life of each bubble is so short that any detailed study of cavity formation and collapse necessitates that exceedingly high frame rates be used; thus it is suggested that future study upon this phase of cavitation be made with high speed motion pictures.

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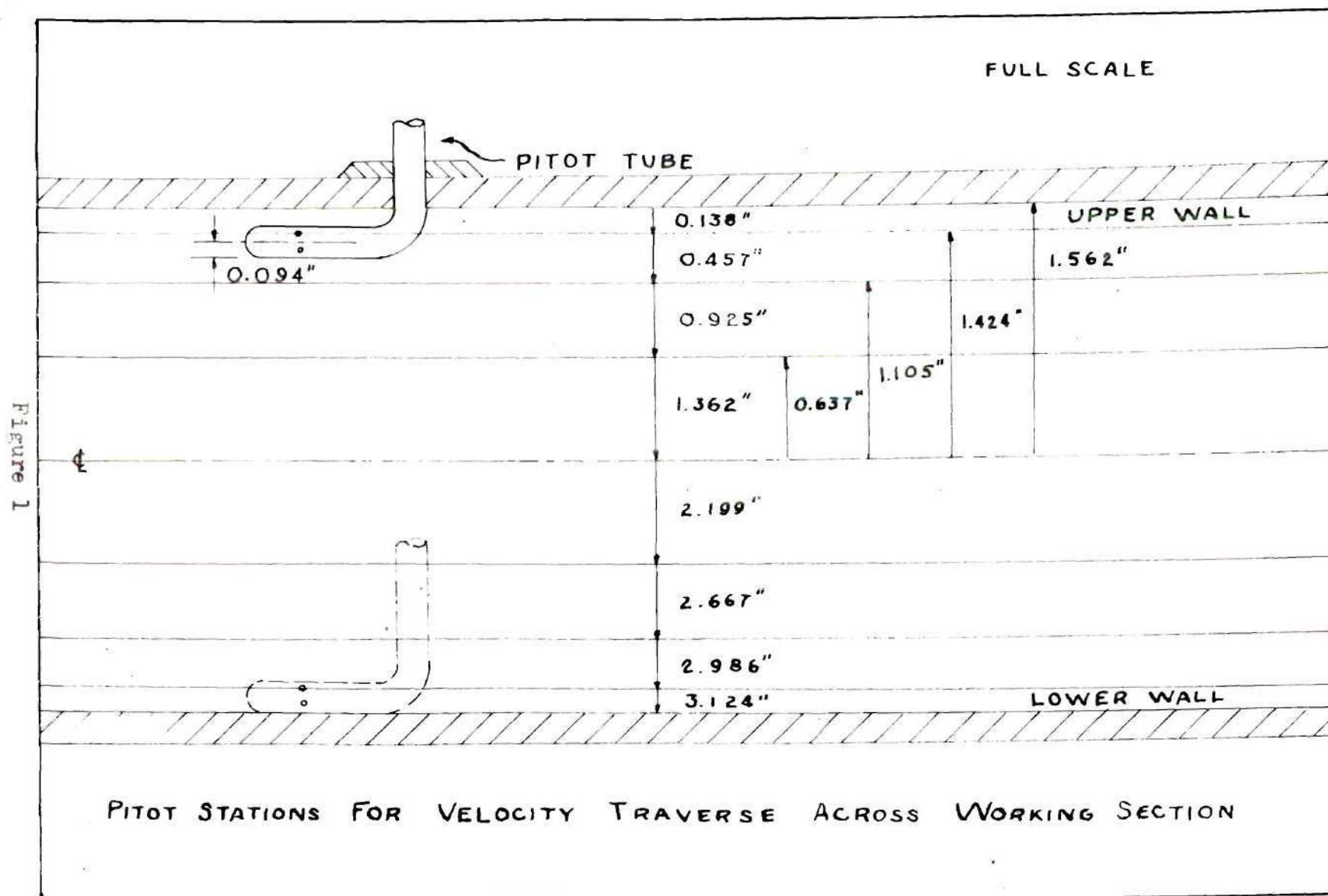
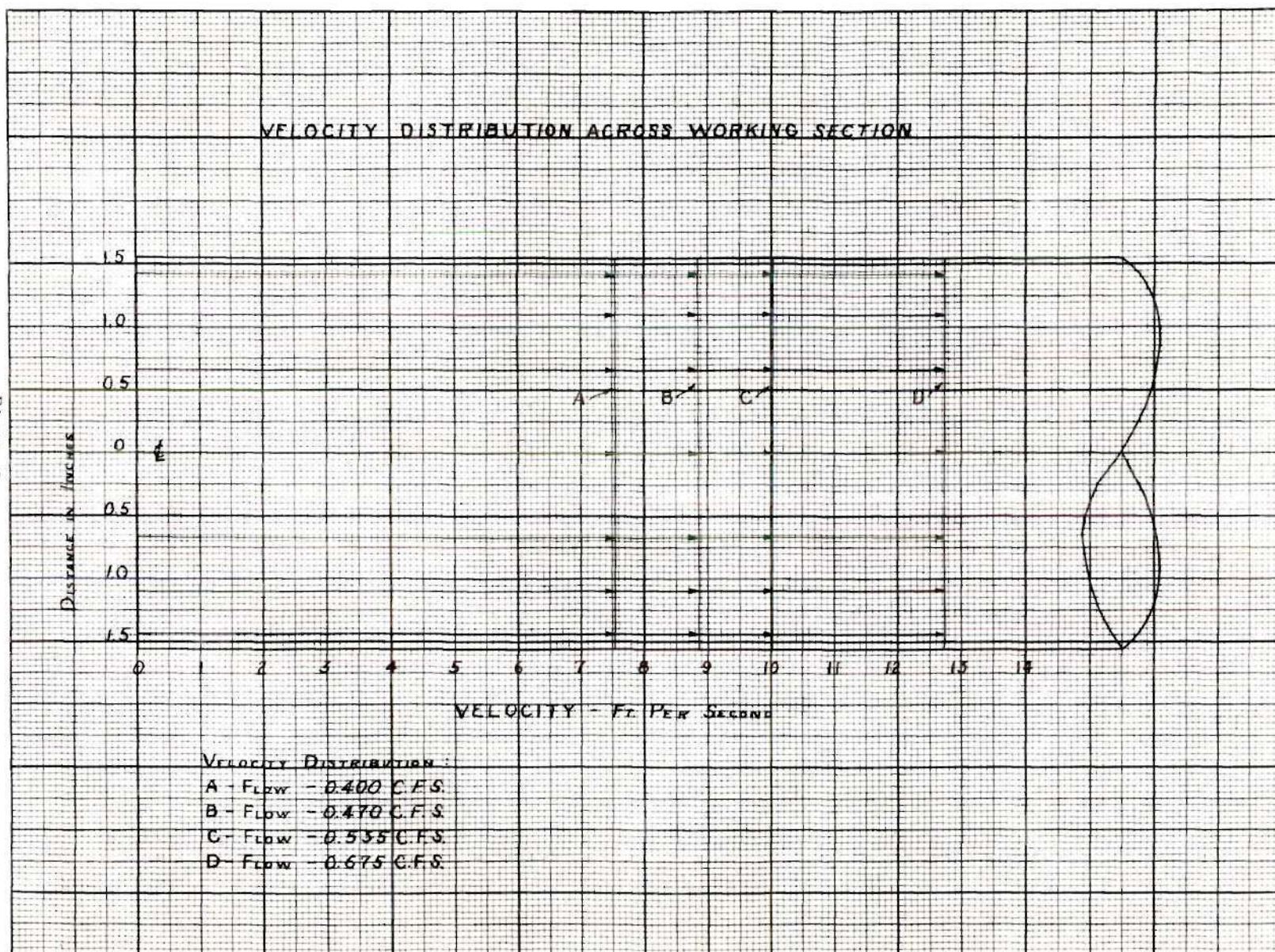


Figure 2



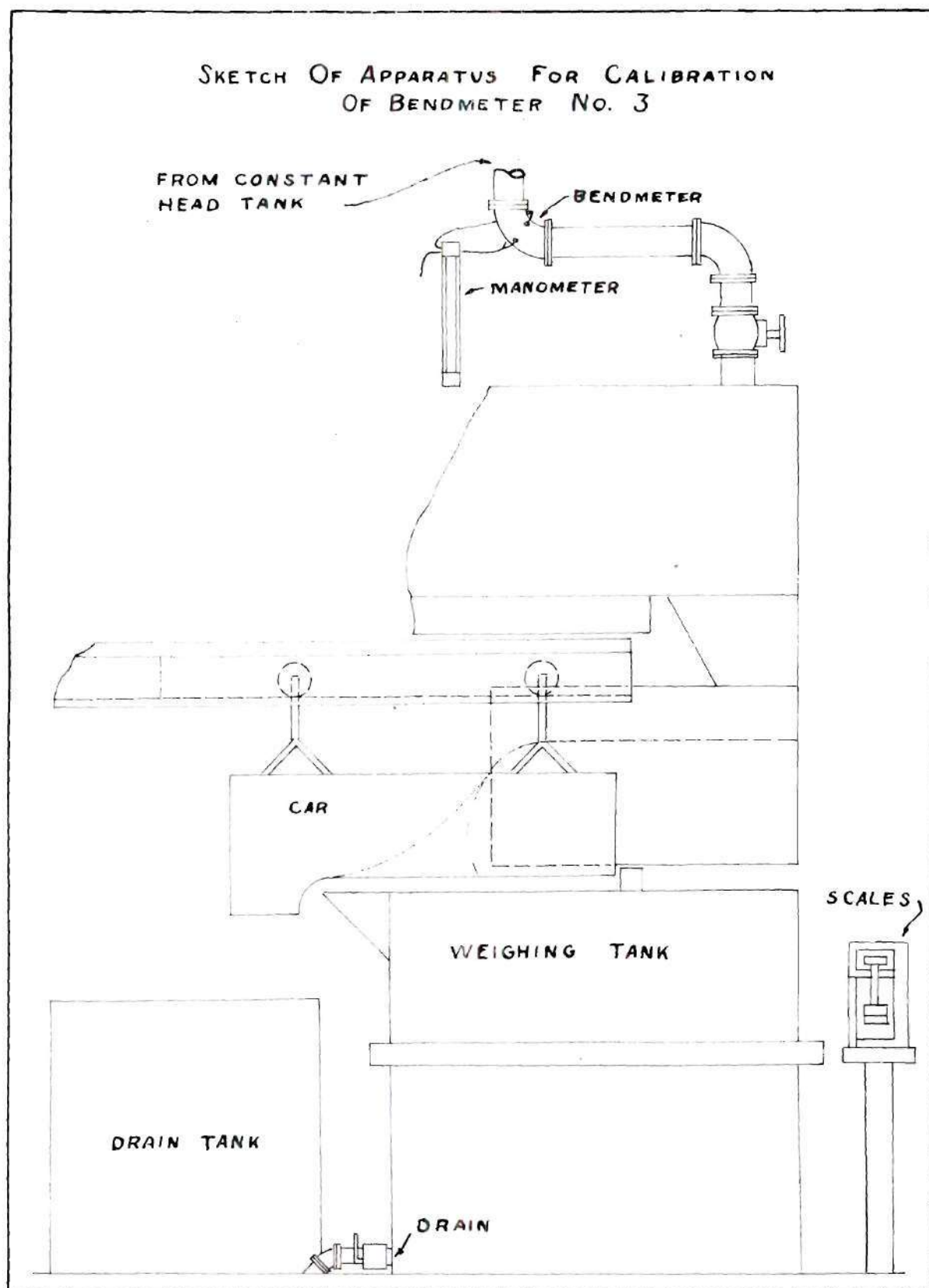


Figure 3

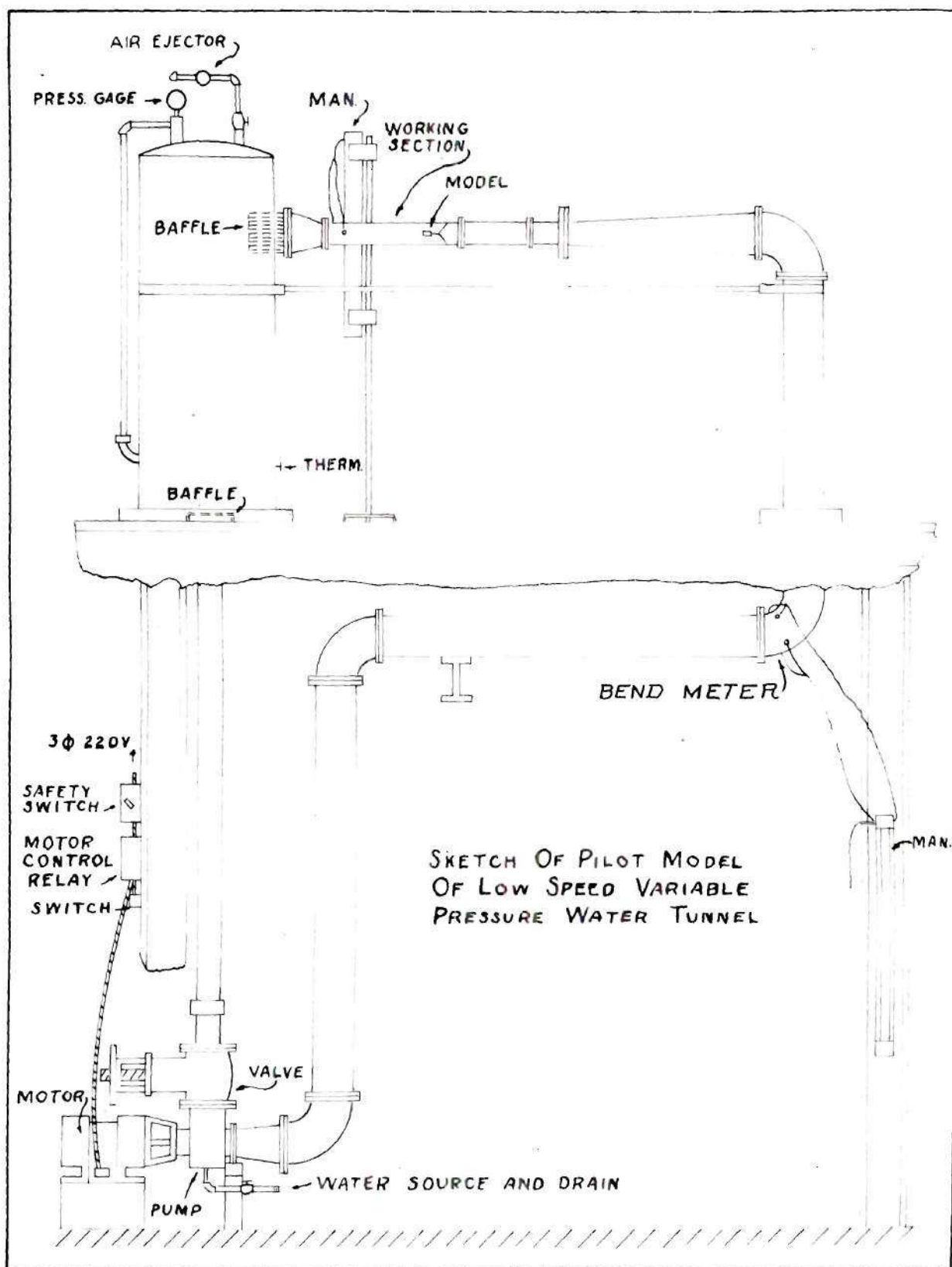


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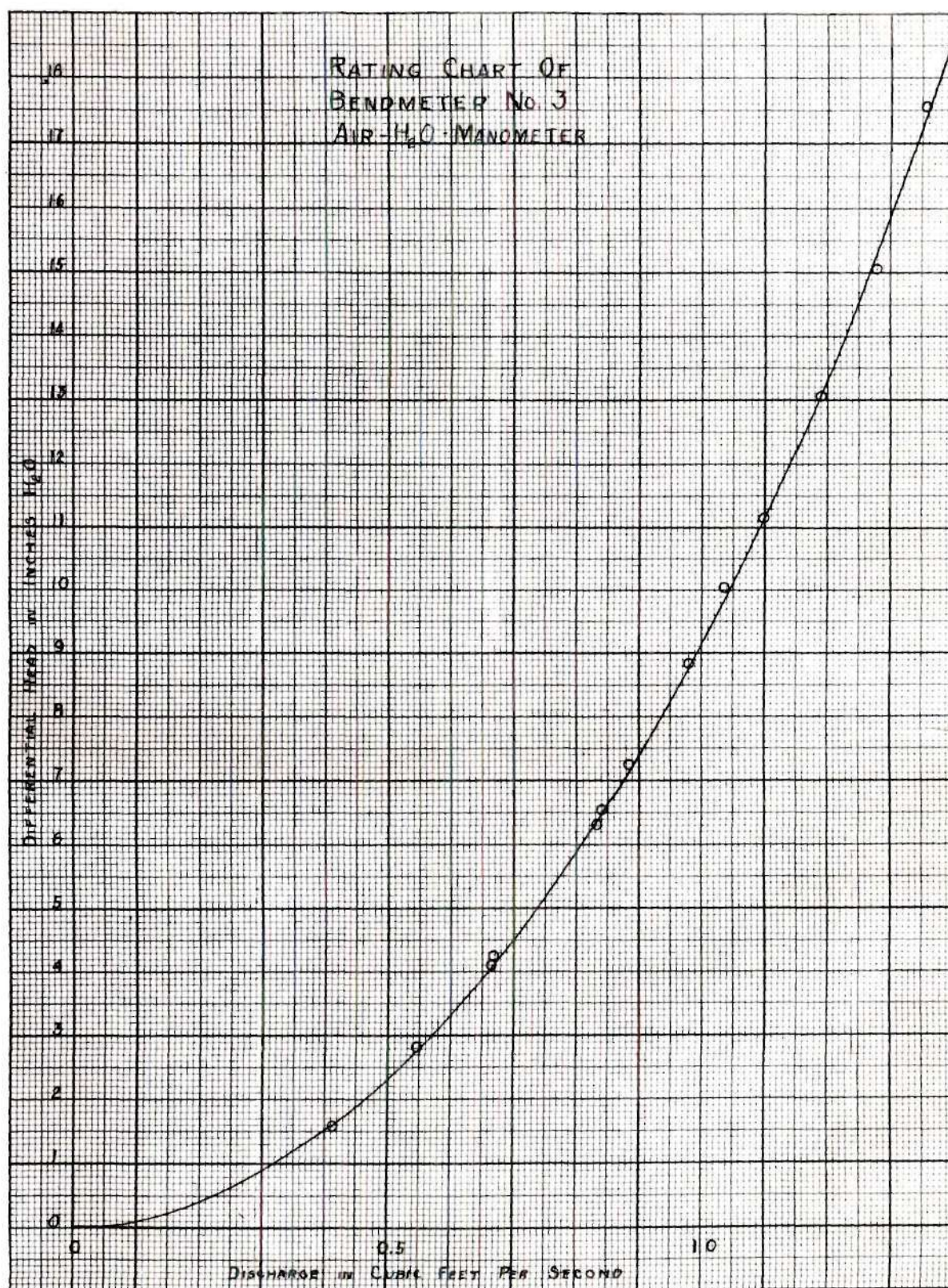


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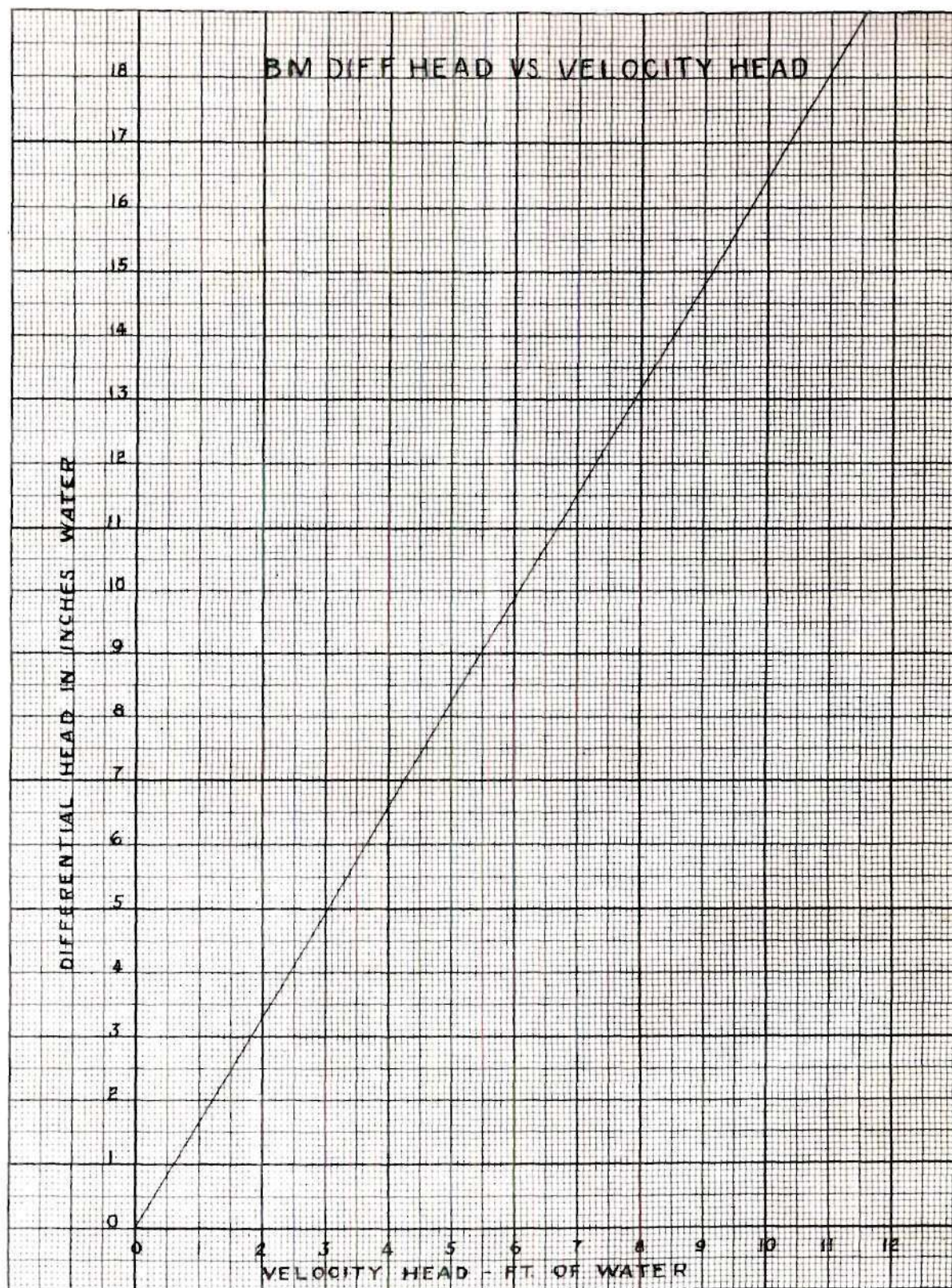


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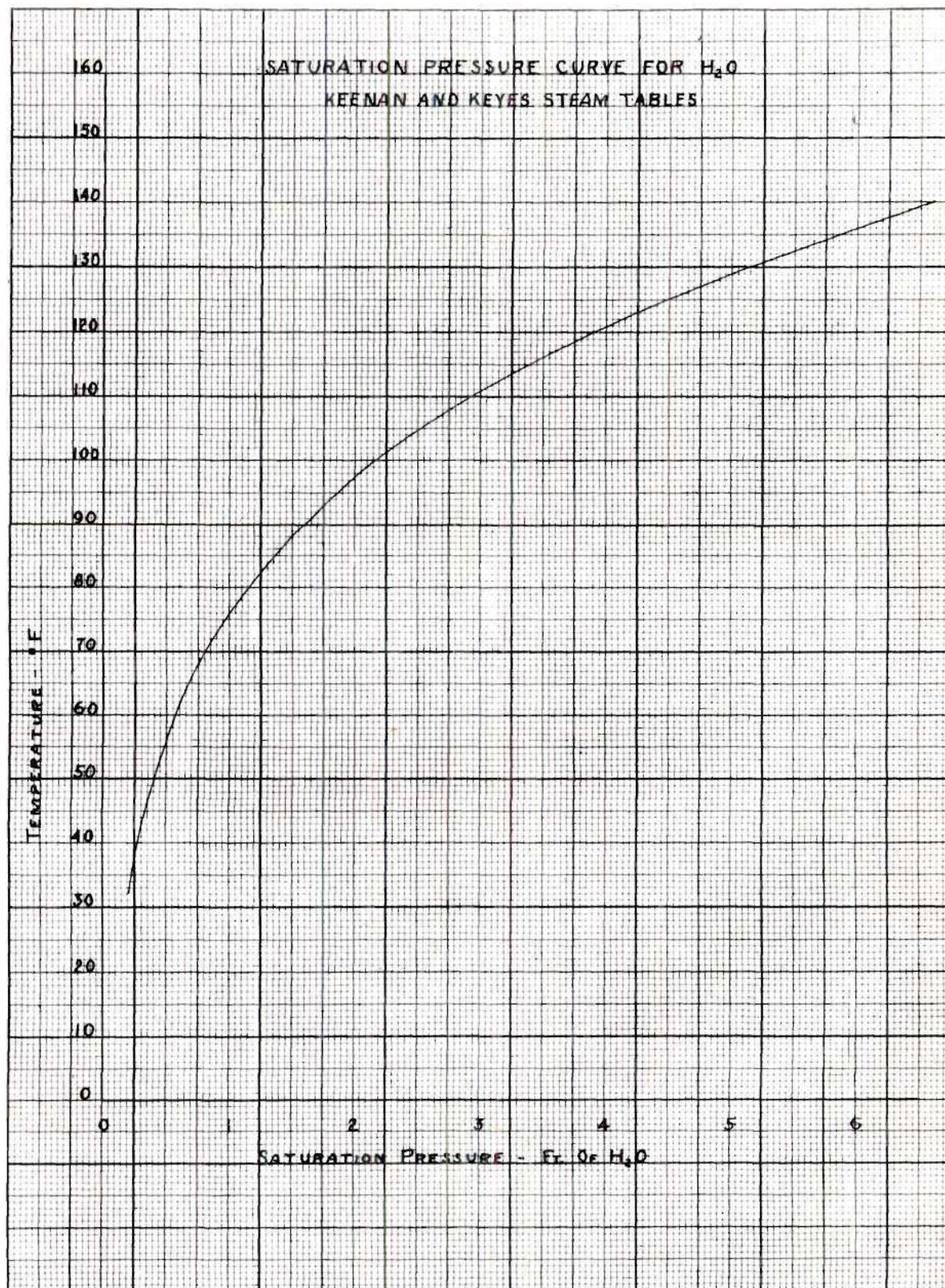


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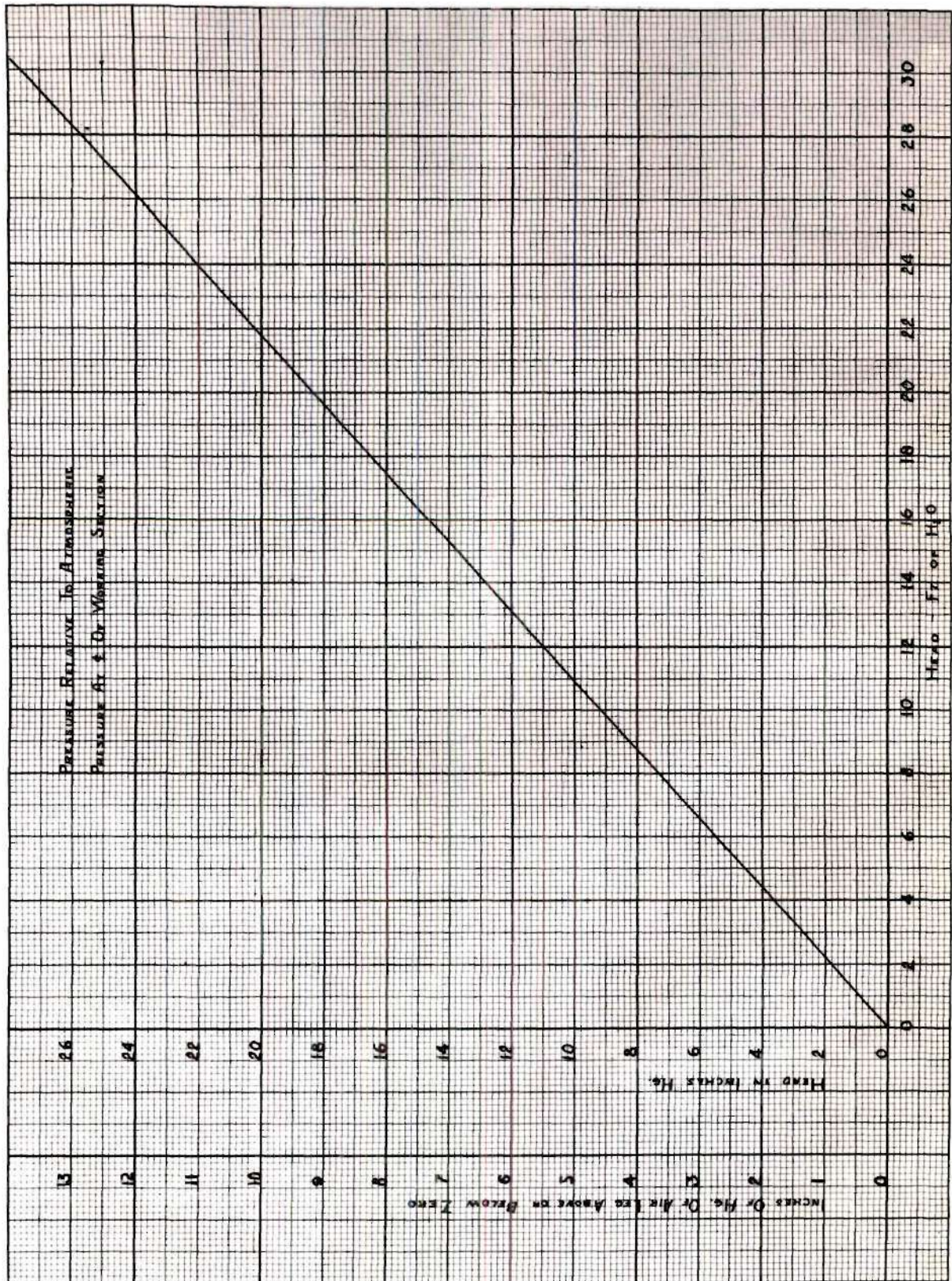


Figure 8

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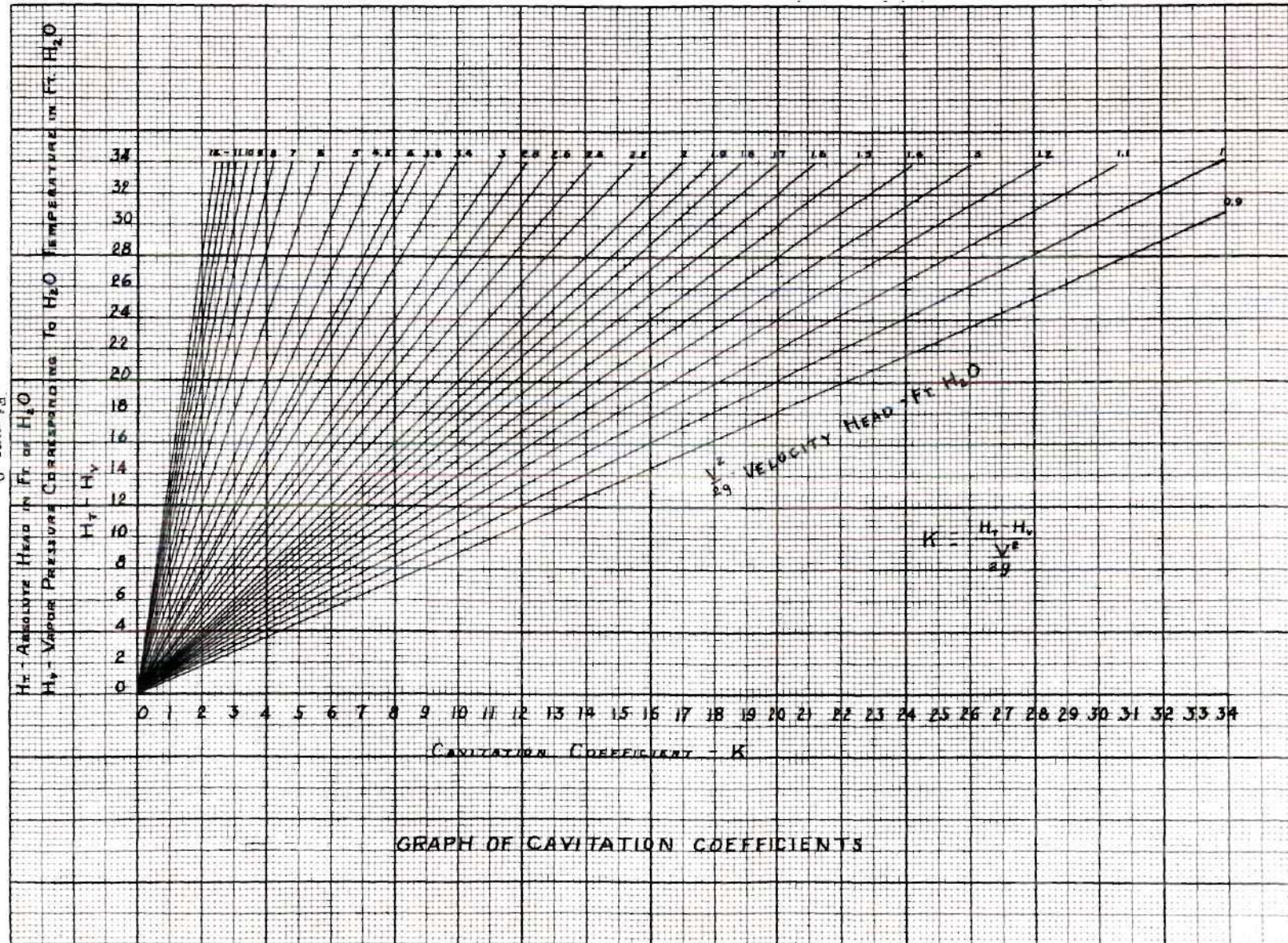
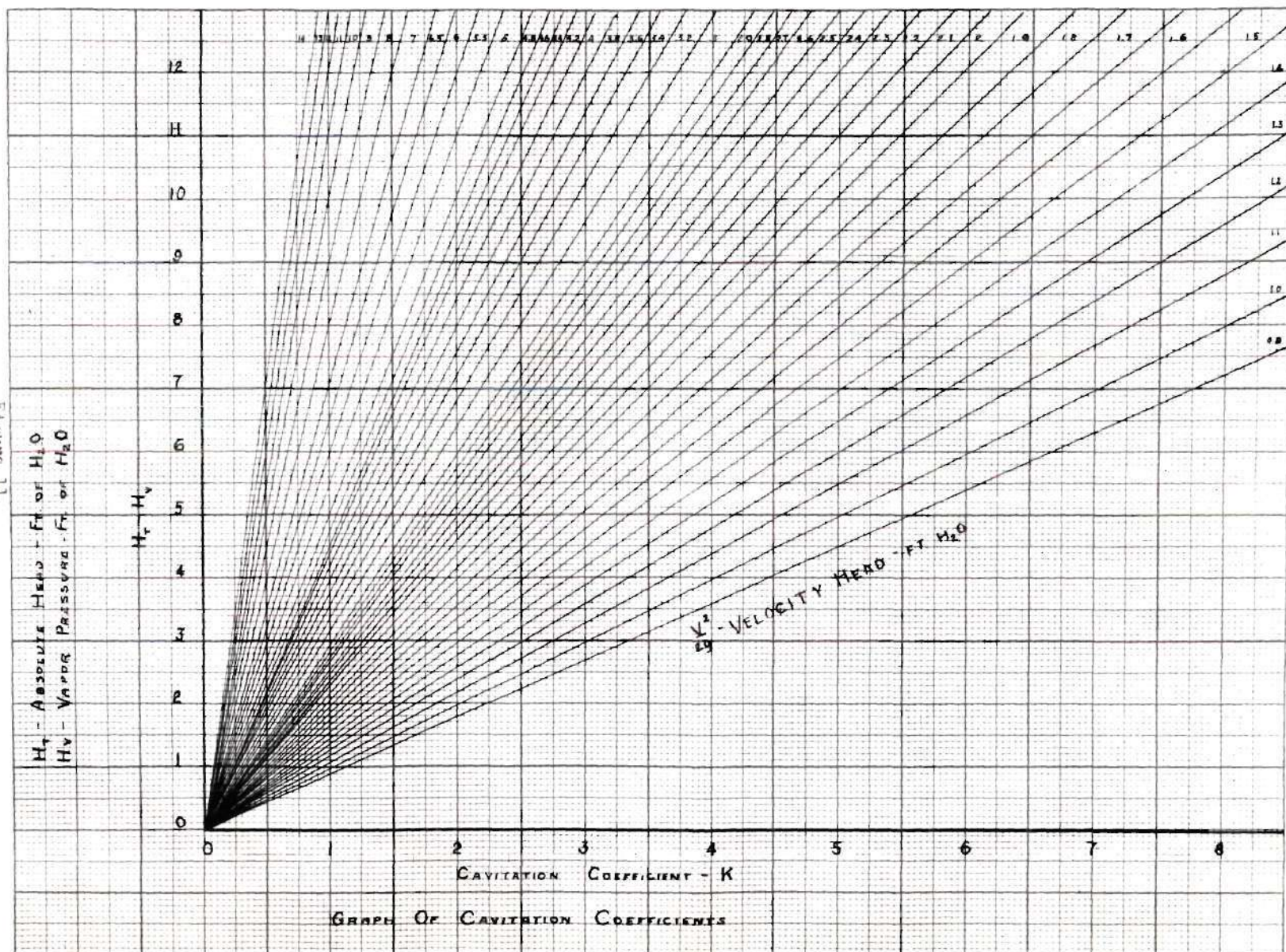


Figure 11



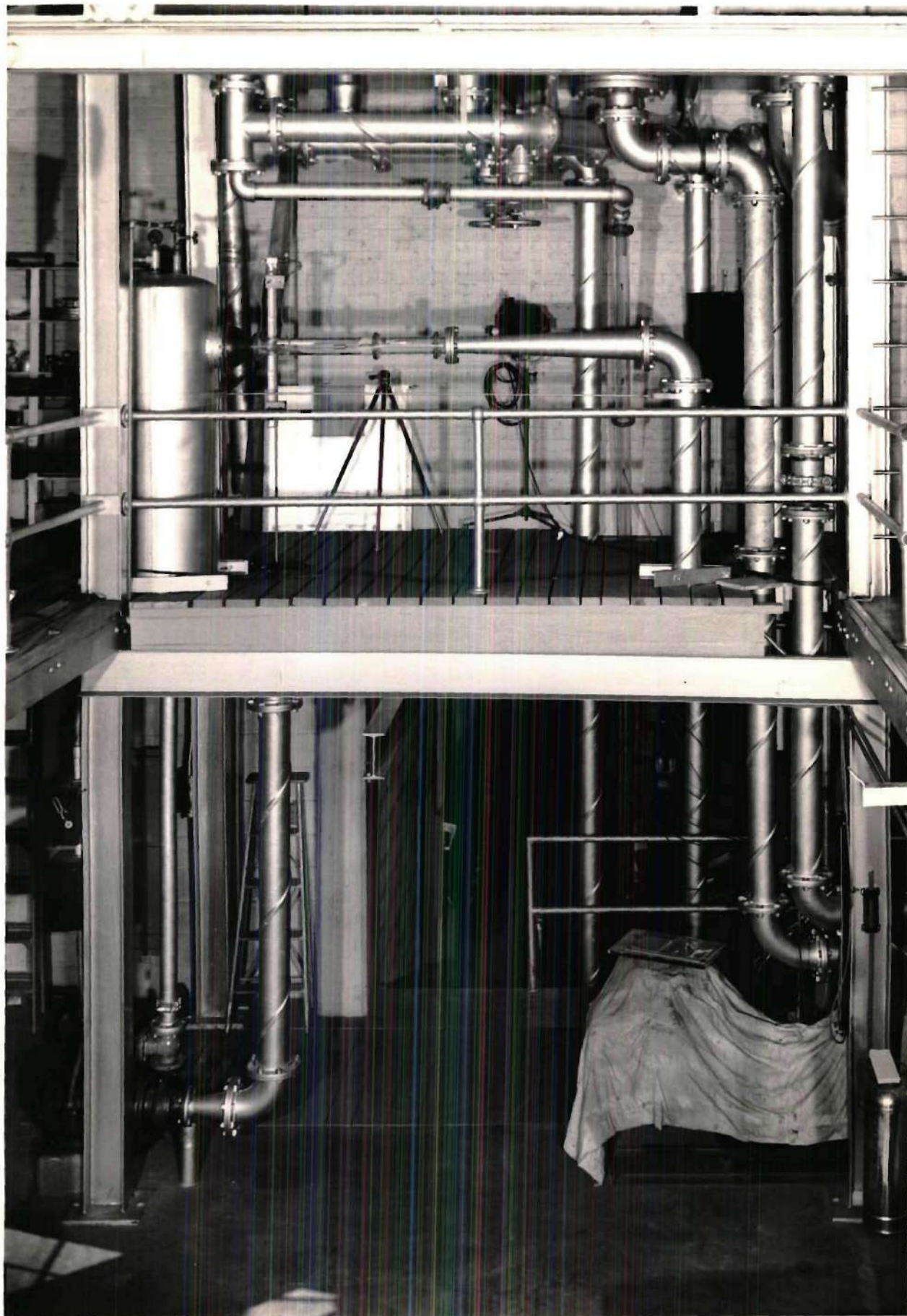


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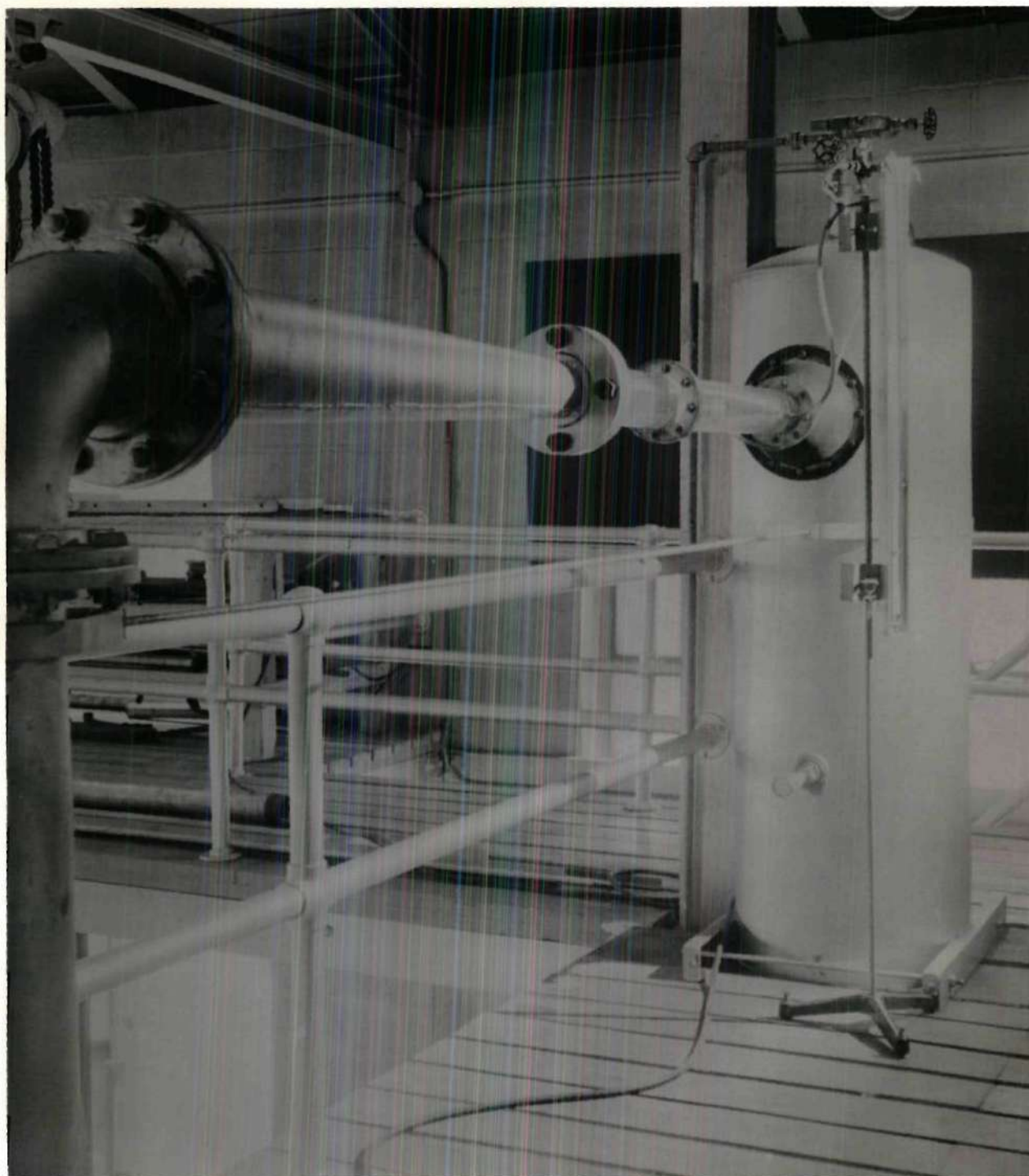


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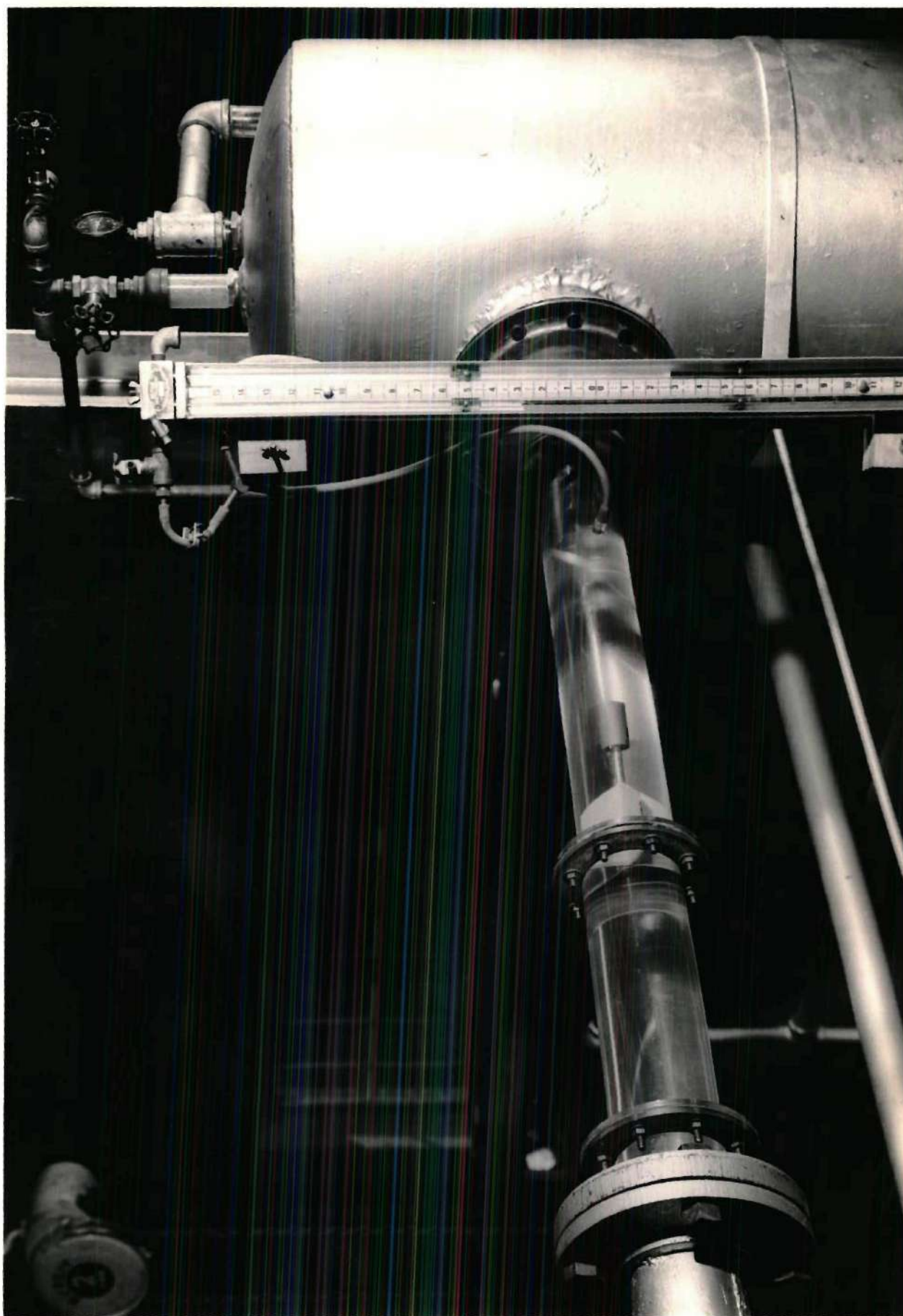


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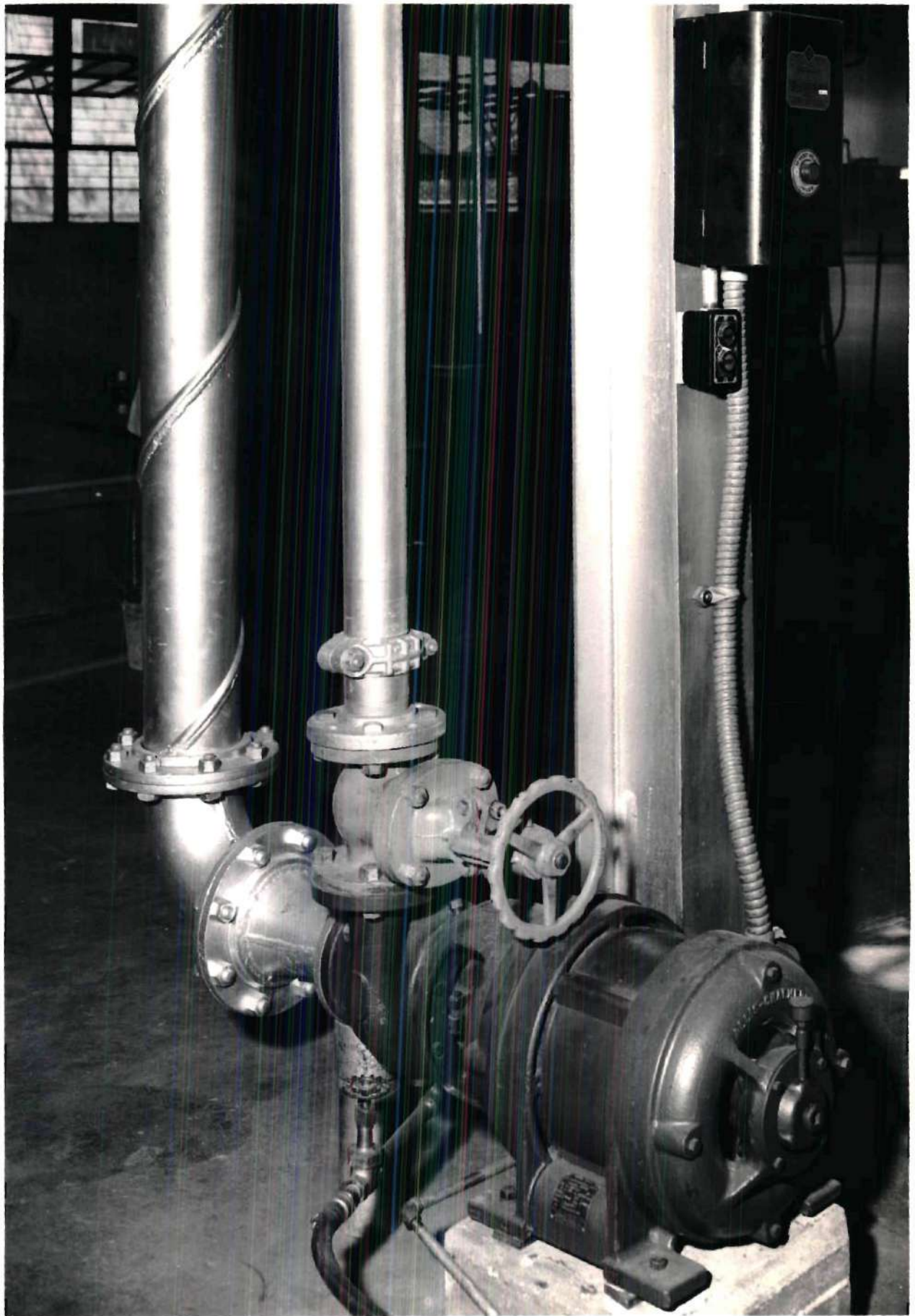


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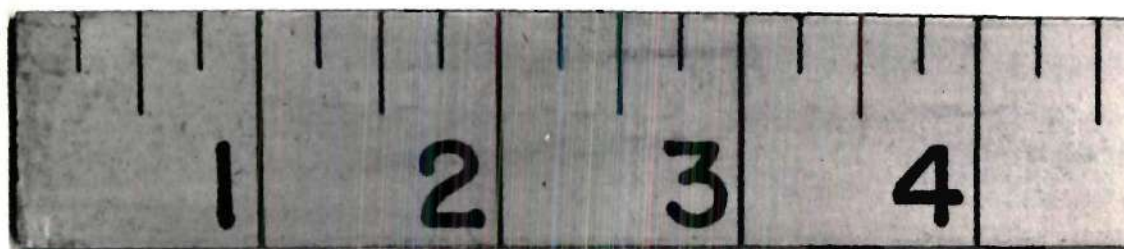


Figure 16.



Figure 17.



Figure 18.



Figure 19.

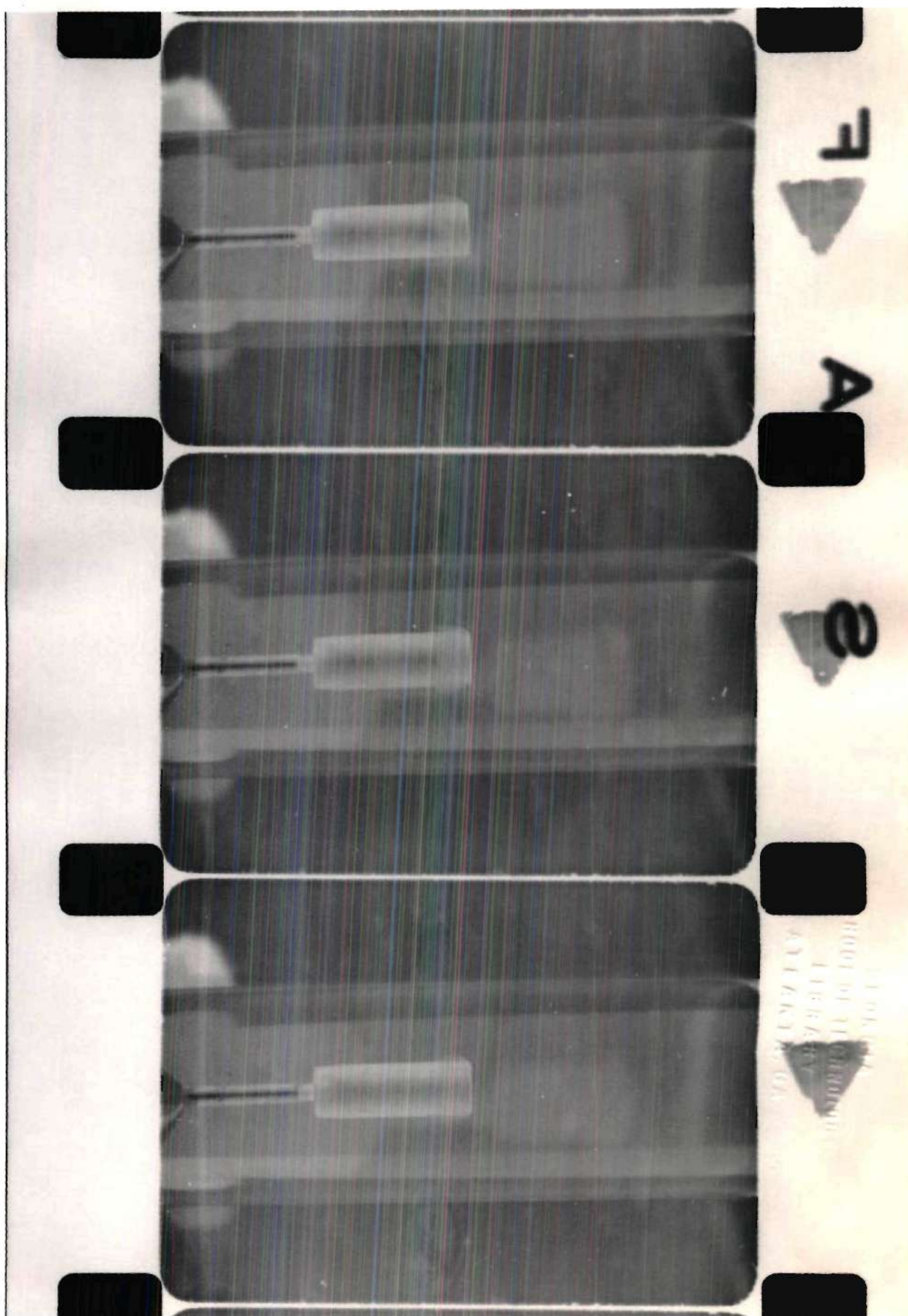


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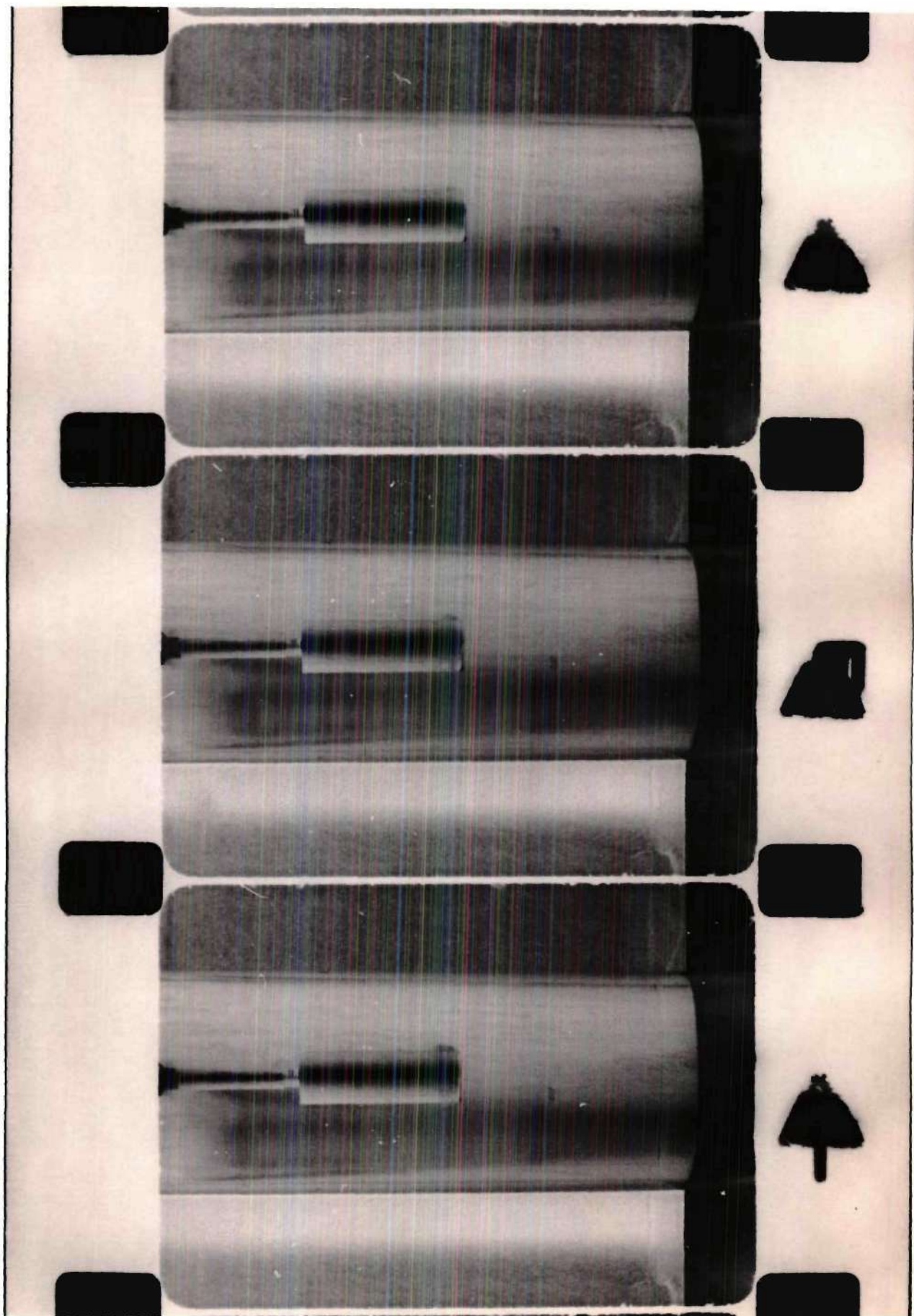


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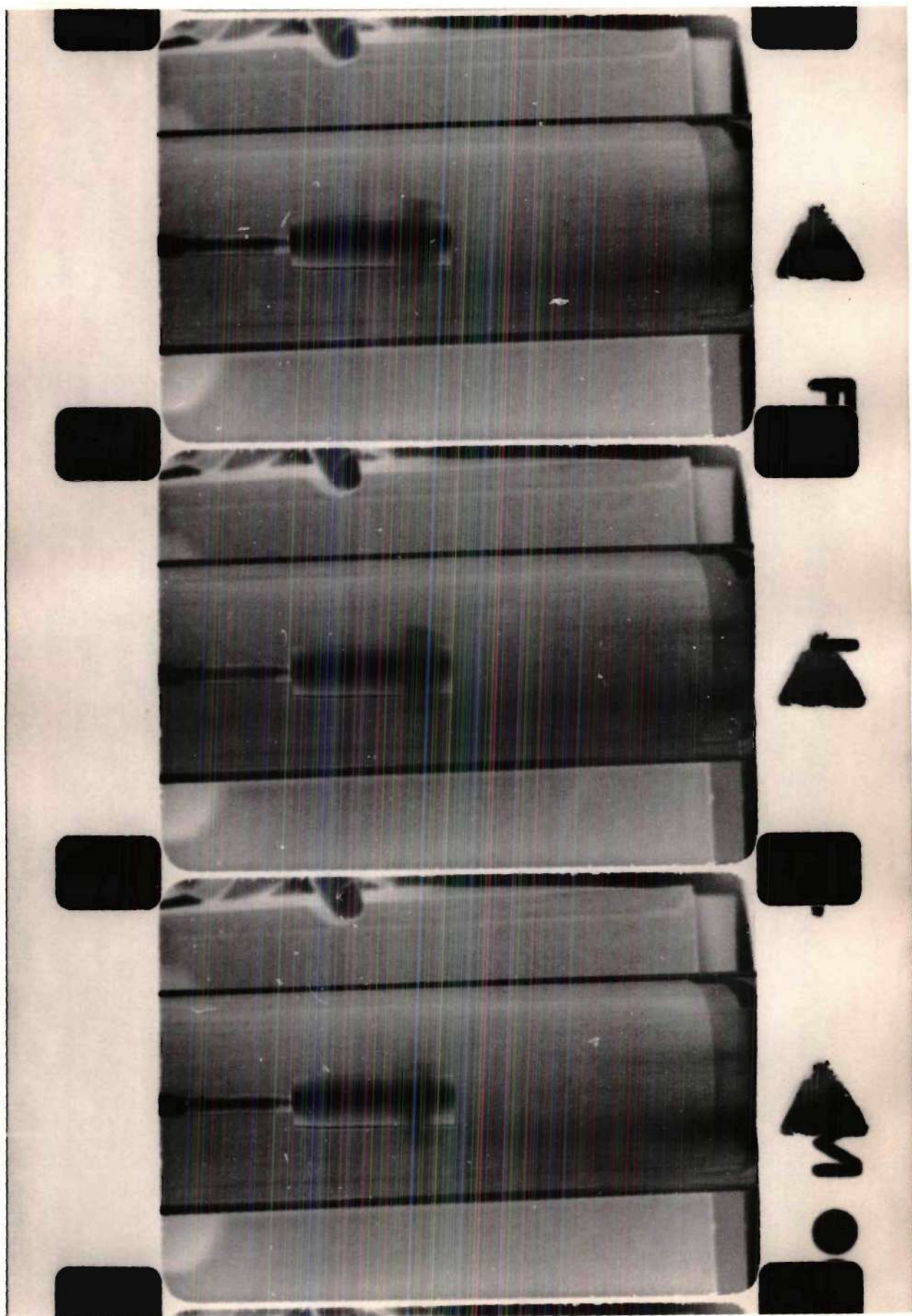


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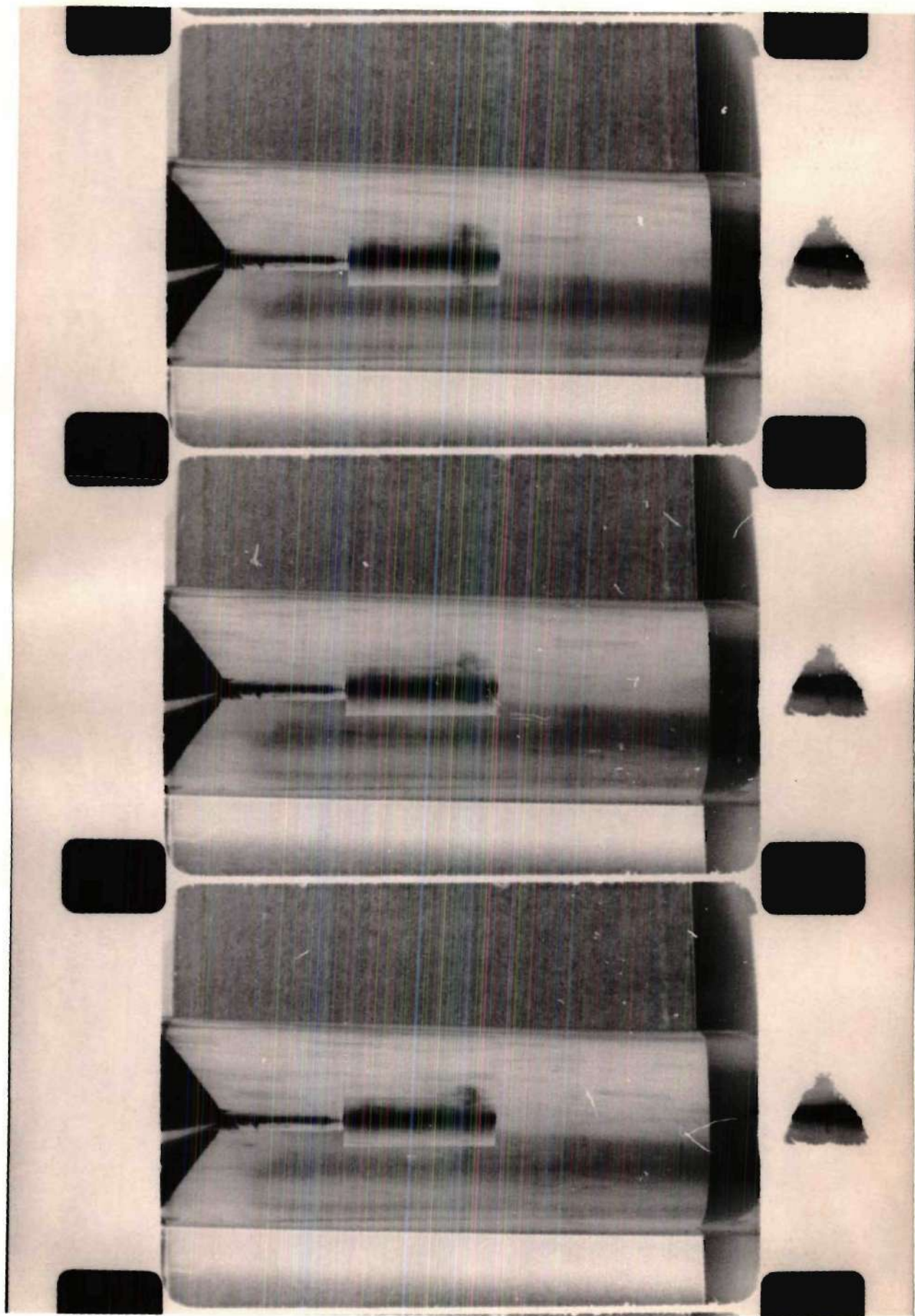


Figure 23.